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PINGU and the neutrino mass hierarchy: Statistical and systematical aspects

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Summary. — The proposed PINGU project (Precision IceCube Next Generation Upgrade) is supposed to determine neutrino mass hierarchy through matter effects of atmospheric neutrinos crossing the Earth core and mantle, which leads to variations in the events spectrum in energy and zenith angle. The presence of non-negligible (and partly unknown) systematics on the spectral shape can make the statistical analysis particularly challenging in the limit of high statistics. Assuming plausible spectral shape uncertainties at the percent level (due to effective volume, cross section, resolution functions, oscillation parameters, etc.), we obtain a significant reduction in the sensitivity to the hierarchy. The obtained results show the importance of a dedicated research program aimed at a better characterization and reduction of the uncertainties in future high-statistics experiments with atmospheric neutrinos.

1. – Introduction

Currently, the global analysis of neutrino oscillation data [1] shows no significant preference for either neutrino mass hierarchies (normal or inverted). Among the methods proposed to measure this unknown parameter there is high statistics atmospheric neutrino oscillations, *e.g.* PINGU [2] (Precision IceCube Next Generation Upgrade). In this context, sub-horizon neutrinos crossing the Earth mantle and core can show θ_{13}-resonance effects in their oscillation probabilities. This effect enhances the effective mixing angle in matter with respect to the one in vacuum, but it can only occur for neutrinos if the hierarchy is the normal one, and for antineutrinos in the opposit case. Despite not being able to distinguish ν from $\bar{\nu}$, PINGU has still a residual sensitivity to the mass hierarchy, beacuse of the different cross sections for ν and $\bar{\nu}$.

Analyses of mass hierarchy sensitivity from atmospheric neutrino experiments, taking PINGU as a case study, have been already performed in [3-7]. They showed that PINGU can reach a sensitivity of at least a few standard deviations in a few years, especially in favorable conditions for large matter effects (*i.e.*, for normal hierarchy and

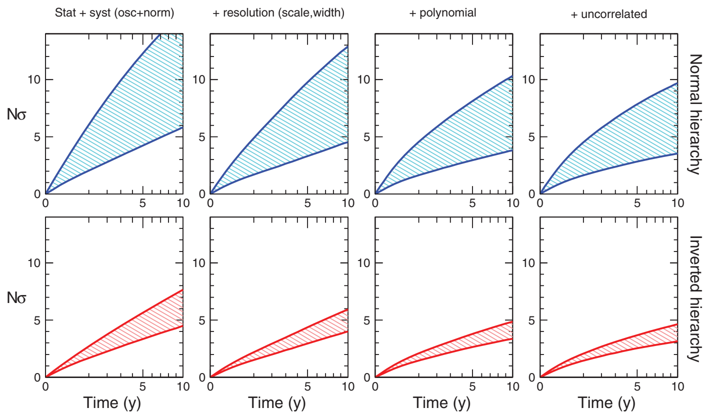

Fig. 1. – PINGU hierarchy sensitivity as a function of detector live time T in the case of normal hierarchy true (top row) and inverted hierarchy true (bottom row). The colored bands are obtained by varying $\sin^2\theta_{23}$(true) in the interval [0.4,0.6]. Each column refers to a different set of systematic errors as specified in the text.

the mixing angle θ_{23} in the second octant). However, so far only a few systematics have been considered, including uncertainties on the oscillation parameters, electron density, normalization of neutrino fluxes, energy scale and resolution functions width. With only these uncertainties, the differences between event spectra calculated for opposite hierarchies are O(few%), depending mainly on true hierarchy and θ_{23} octant, and can be further reduced by considering additional systematic shape deviations at the percent level. The source of other systematic errors is connected to uncertainties (both energy and zenith-angle dependent) on effective volume, neutrino fluxes, cross sections and on numerical approximations. In sect. 2 we describe some general features of the statistical analysis of PINGU prospective data and we analyze the impact of shape systematics on the PINGU sensitivity to hierarchy.

2. – Statistical analysis and results

Here we report just the main features of the statistical analysis (a more detailed description is in [8]). The analysis is performed using the "pull method" [9], which requires a linear expansion of N^{α}_{ij} (number of expected events in the ij-th bin for ν_α, with $\alpha = e, \mu$) under small deviations of systematical parameters. Because the linearization is not valid for $\sin^2\theta_{23}$ and for the CP phase δ, for any given choice of true hierarchy parameters $(\sin^2\theta_{23}, \delta)$, we scan the wrong hierarchy parameters $(\sin^2\tilde{\theta}_{23}, \tilde{\delta})$ over a grid sampling the full range $[0,\, 1] \otimes [0, 2\pi]$.

As far as spectral perturbations are concerned, in the absence of dedicated studies, we assume a polynomial function in E (neutrino energy) and θ (zenith angle), multiplying N^{α}_{ij} (number of expected events in the ij-th bin for ν_α, with $\alpha = e, \mu$), independently for muon and electron neutrinos. We find convergence of results at fourth order polynomial. The coefficients are allowed to float around a null central value within representative fractional errors, that we choose to be 1.5% (default), 0.75% (halved), 3.0% (doubled). We take into account also possible residual uncorrelated errors of reasonable size in each bin, which lead to finite $\Delta\chi^2$ values in the limit of infinite statistics. We assume the same error size adopted for polynomial coefficients.

Figure 1 shows how the PINGU hierarchy sensitivity ($N\sigma = \sqrt{\Delta\chi^2}$) varies as a function of the detector live time T in years. The bands cover the fit results obtained by spanning the range $\sin^2\theta_{23}(\text{true}) \in [0.4, 0.6]$. The abscissa is scaled as $\sqrt{T}$, so that the bands would grow linearly in the ideal case of no systematic errors (not shown). From left to right, the fit includes the following systematic errors: oscillation and normalization uncertainties, energy scale and resolution width errors, polynomial shape systematics (with up to quartic terms), and uncorrelated systematics. The last two error sources are kept at the default level of 1.5%.

The progressive inclusion of correlated shape systematics, both "known" (resolution scale and widths) and "unknown" (ad hoc polynomial deviations), and eventually of uncorrelated shape systematics, provide a suppression of $N\sigma$, whose estimated ranges increase more slowly than $\sqrt{T}$. The typical effect of all the systematic shape errors in the rightmost panels is to decrease the 5-year (10-year) PINGU sensitivity by up to 35% (40%), with respect to the leftmost panels in fig. 1. Considering halved and doubled erros on shape uncertainties, the reduction of the hierarchy sensitivity varies from 20% to 50%.

3. – Conclusions

The results suggest that PINGU is sensitive to spectral systematics of O(few %). These uncertainties require a careful investigation, since they may be able to lower the PINGU sensitivity from 20% to 50%, as compared with analyses including only the most obvious systematics due to oscillation and normalization uncertainties.

Breaking down such uncertainties into separate nuisance parameters is of paramount importance in order to have an accurate estimate of the spectral "flexibility", which affects the hierarchy sensitivity. Furthermore, in the limit of very high statistics, one should also take into account residual correlated and uncorrelated systematic uncertainties, which may not have a well-defined parametrization. This research effort, already considered in other fields, would be beneficial not only for the PINGU project, but also for future high statistics atmospheric experiments such as ORCA [10], INO [11] and HyperKamiokande [12].

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